Regaining Lost Separation in a Piloted Simulation of Autonomous Aircraft Operations

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Abstract

NASA is currently investigating a new concept of operations for the National Airspace System, designed to improve capacity while maintaining or improving current levels of safety. This concept, known as Distributed Air/ Ground Traffic Management (DAG-TM), allows appropriately equipped "autonomous" aircraft to maneuver freely for flight optimization while resolving conflicts with other traffic and staying out of special use airspace and hazardous weather. While Airborne Separation Assurance System (ASAS) tools would normally allow pilots to resolve conflicts before they become hazardous, evaluation of system performance in sudden, near-term conflicts is needed in order to determine concept feasibility. If an acceptable safety level can be demonstrated in these situations, then operations may be conducted with lower separation minimums.

An experiment was conducted in NASA Langley's Air Traffic Operations Lab to address issues associated with resolving near-term conflicts and the potential use of lower separation minimums. Sixteen commercial airline pilots flew a total of 32 traffic scenarios that required them to use prototype ASAS tools to resolve close range "pop-up" conflicts. Required separation standards were set at either 3 or 5 NM lateral spacing, with 1000 ft vertical separation being used for both cases. Reducing the lateral separation from 5 to 3 NM did not appear to increase operational risk, as indicated by the proximity to the intruder aircraft. Pilots performed better when they followed tactical guidance cues provided by ASAS than when they didn't follow the guidance. As air-air separation concepts are evolved, further studies will consider integration issues between ASAS and existing Airborne Collision Avoidance Systems (ACAS).

Introduction

NASA is investigating a radically new concept of operations for the future National Airspace System (NAS). This concept, known as *Distributed Air/Ground Traffic Management* (DAG-TM), enables pilots flying appropriately equipped "autonomous" aircraft to have more flexibility in choosing optimal flight trajectories while simultaneously resolving conflicts with other aircraft, special use airspace, and hazardous weather [1]. Air Traffic Service Providers still provide constraints in this concept when needed to meet local traffic flow management needs and also provide traffic separation services to those aircraft unable to participate in autonomous operations. A critical component to the feasibility of DAG-TM operations is the effectiveness of an Airborne Separation Assurance System (ASAS) aboard the autonomous aircraft.

Separation assurance systems would normally enable pilots operating in a DAG-TM environment to respond to traffic conflict situations well before the conflicting aircraft poses a hazard to safe flight. Previous studies have shown that pilots are able to use prototype ASAS tools effectively to resolve longer-term conflicts [2-3].

One can envision situations that may arise, however, that do not allow this normal opportunity for strategic decision-making. Various non-normal events could require the autonomous aircraft pilot to use the ASAS system to resolve a near-term conflict. Examples may include an aircraft forced to descend rapidly due to a loss of cabin pressure or an improper maneuver by an aircraft responding to another conflict. Demonstration of a pilot's ability to effectively use ASAS to resolve near-term conflicts and regain lost separation is needed in order to assess concept feasibility.

These types of non-normal events will require the ASAS to provide effective alerts and resolutions prior to the time that an Airborne Collision Avoidance System (ACAS) would give a Resolution Advisory (RA). When an RA is issued, a pilot must take immediate action in order to avoid a potential near miss. The Traffic Alert and Collision Avoidance System (TCAS) II currently functions as an ACAS aboard commercial aircraft. Depending on the own aircraft's altitude, RA's are only issued 15-35 seconds prior to the Closest Point of Approach (CPA) [4]. Prior to an RA, DAG-TM pilots operating autonomous aircraft must rely solely on ASAS for resolution guidance.

An additional area of DAG-TM concept feasibility relates to a potential reduction in separation standards. Lower separation standards are likely needed in order to improve NAS efficiency and capacity [5-6]. Current separation minimums are based in large part on the capabilities of older radar systems [7]. Safety assessments are needed to determine the feasibility of reduced separation minimums. They will give strong consideration to surveillance system performance, including accuracy, integrity, and availability [8-10]. Candidate surveillance systems include Automatic Dependent Surveillance-Broadcast (ADS-B) and multi-lateration systems. Considering studies done for Reduced Vertical Separation Minimums (RVSM) operations, it is likely that flight technical errors will also be considered [11-12].

In addition to a thorough evaluation of surveillance system performance, a potential decision to lower the separation standards should also take operational considerations into account. An ASAS Safety Assessment study identified improper maneuvering in response to a conflict (due to ambiguous or improper resolution commands or a pilot's failure to comply with the resolution) as a potential safety risk [9]. If near-term conflicts with lower separation minimums were determined to be more challenging for pilots, the severity of these risks could be even greater.

An experiment was conducted in NASA Langley's Air Traffic Operations Lab to address issues related to ASAS use for near-term conflicts with a potential reduction in separation minimums. The experiment had the following two primary objectives:

- Evaluate the effectiveness of prototype ASAS tools in enabling the pilot to safely resolve near-term conflicts.

- Compare the effect of 3 and 5 NM lateral separation standards (with 1000 ft vertical separation) on a pilot's ability to safely resolve near-term traffic conflicts.

The experiment was part of a series of ongoing air-air separation assurance studies, including previous work presented at the 4th USA/Europe Air Traffic Management R&D Seminar [3].

Experimental Approach

Air Traffic Operations Lab

The Air Traffic Operations Lab at NASA Langley is a medium fidelity PC workstation-based facility, enabling simultaneous operation by up to 8 subject pilots. Each pilot station consists of a transport aircraft model and flight deck displays designed to replicate the MD-11. Figure 1 shows the display and flight control suite made available to the pilots during the experiment. Traffic information was superimposed on the navigation display and pilots were provided with a Navigation Display Control Panel (NDCP) to adjust the display's traffic specific features. The NDCP was located to the left of the Glareshield Control Panel. All control of the simulation aircraft was done through the Glareshield Control Panel and Multifunction Control Display Unit (MCDU) associated with the Flight Management System (FMS). No manual flight control was available.

Figure 1. Pilot Displays and Control Panels
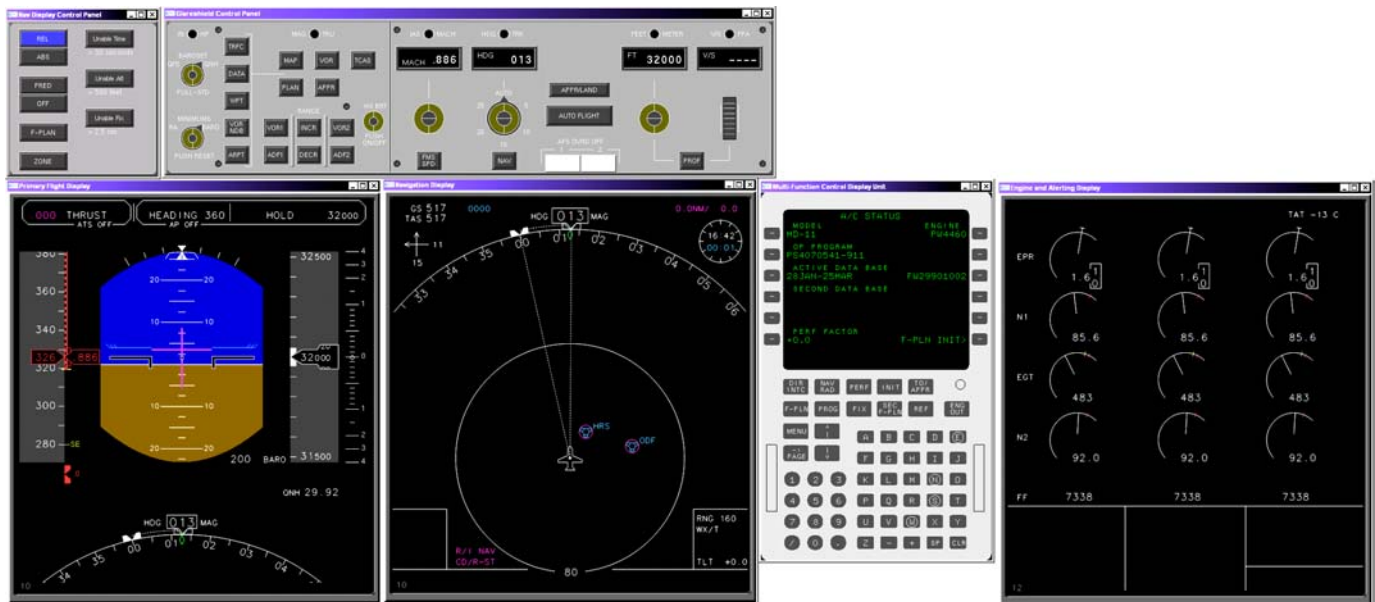
Subjects

Sixteen commercial airline pilots with experience in Airbus glass cockpit or MD-11 aircraft participated in the experiment. All were active pilots or had retired within the previous year. Their ages ranged from 32 to 57 and flight experience ranged from 4,200 to 23,000 hours.

Design

The experiment used a single-factor within-subjects design. This factor was the required lateral separation from other aircraft and was set at either 3 or 5 NM. The required vertical separation was 1000 ft for both cases.

Pilots flew one scenario for each lateral separation condition and each scenario had one designed near-term conflict. Although other background aircraft were present, the data analysis only considered the designed conflict. Scenarios for the lateral separation condition were counterbalanced for order and were included as part of a larger study that consisted of nine scenarios flown per pilot. Several of the other seven scenarios were run in between those for this experiment, in order to help prevent the pilot from anticipating the designed conflict. This paper only discusses results from the two near-term conflict scenarios.

Scenario Set-up and Pilot Tasks

All pilots were flying autonomous aircraft in a DAG-TM en-route environment and were asked to maintain standard separation from other air traffic and from restricted airspace. Pilots were allowed to maneuver freely without contacting a controller. This experiment focused only on air-air separation assurance involving "autonomous" aircraft and the simulation did not incorporate a ground component. Future studies are planned that will look at integrated air-ground applications involving aircraft of mixed equipage.

In addition to maintaining traffic separation, pilots were given a downline waypoint to cross at a Required Time of Arrival (RTA). En route to the RTA, the aircraft's programmed flight path went through a 65 NM wide corridor with restricted airspace areas on each side. Pilots were asked to continue to the RTA waypoint when able after resolving a conflict. The designed conflict occurred about 15 minutes into a 25-minute scenario.

In order to cause a near-term conflict, the designated intruder aircraft was hidden from the subject pilot until just before the predicted loss of separation. At this point, a "pseudo pilot" would turn the intruder toward the subject and turn on the intruder's ADS-B broadcast. It appeared about 6 NM away from and at co-altitude with ownship. An alert occurred shortly thereafter. Pseudo pilots were used to ensure the conflict occurred, even if the subject pilot had deviated from the original programmed flight plan.

Depending on selected map range, the subject pilot could see additional scripted aircraft on the traffic display while en-route to the RTA waypoint. Other traffic was

shown if it was determined to be operationally significant, based on proximity, current trajectory, and intent.

After each scenario, pilots were asked to complete a questionnaire asking them to rate the effectiveness of the traffic alerts and resolution guidance in resolving the conflicts. They were also asked to assess the safety risk posed by the pop-up conflicts.

Displays and Alerts

The prototype ASAS system provided conflict detection, prevention, and resolution based on both state (position, ground speed, and ground track) and FMS-based intent information. ASAS tools were part of larger decision aiding system, known as the Autonomous Operations Planner [13]. TCAS was not available for the experiment.

Traffic alerts were based on outer and inner zones surrounding the aircraft, referred to as the separation and collision zones, respectively (see Figure 2). This design was based on the concept described by RTCA's Airborne Conflict Management (ACM) committee [10]. The separation zone represents the minimum legal separation around an aircraft. It had a 3 or 5 NM radius, depending on the scenario. The vertical dimension was 1000 ft for both cases. A conflict was defined as a predicted loss of separation and a separation violation occurred if an aircraft penetrated another aircraft's separation zone. The collision zone's radius and height above/below were 900 ft and 300 ft, respectively. Penetration of the collision zone was considered to be a near miss.
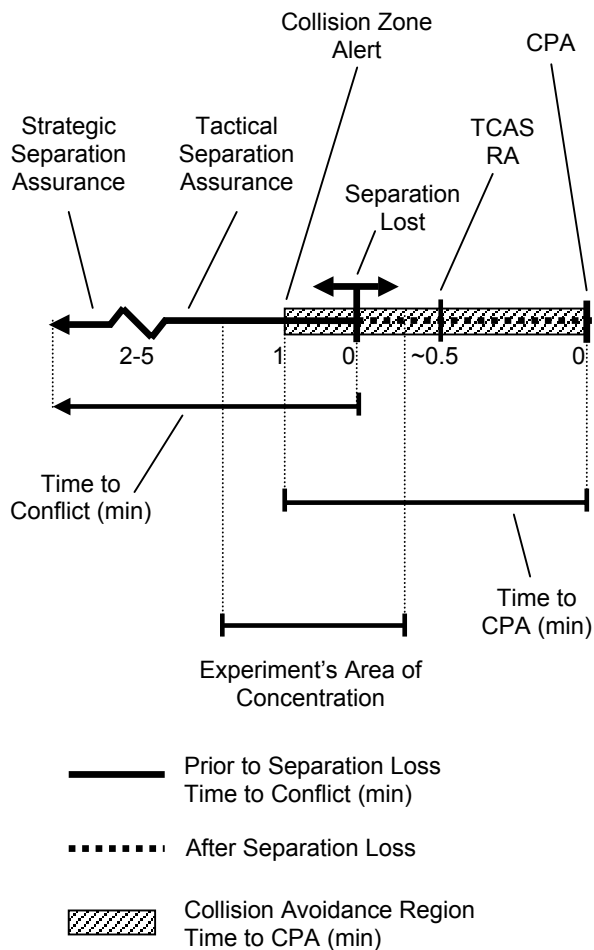
Figure 3 shows a notional timeline for ASAS and ACAS as applied to this experiment. After a conflict was detected but prior to separation loss, ASAS provided information to assist the pilot in maintaining adequate separation. Strategic and/or tactical separation assurance decision support tools were available, depending on the time to conflict. The strategic system was integrated with the FMS to provide an efficient conflict resolution and return to the programmed flight plan. Due to the short timeframe of the planned conflicts, pilots were not able to use the strategic system for this study. Tactical conflict resolutions used only state information and provided recommended changes in heading and/or vertical speed. The transition from the strategic to the tactical mode of operation occurred between 2 and 5 minutes prior to the conflict, which was outside the timeframe of the pop-up traffic. Further details of these systems are provided by Wing et al. [3,14].
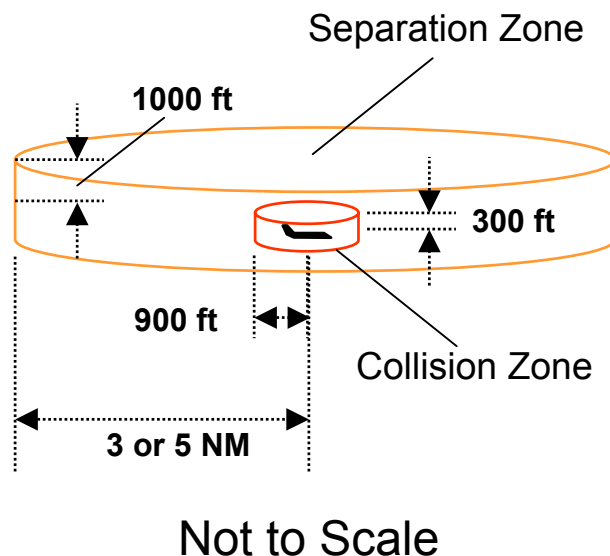
Figure 2. Separation and Collision Zones

If separation was lost, tactical resolutions continued to provide guidance to the pilot on ways to regain the minimum separation. In these cases, pilots were instructed in a pre-flight briefing to follow the tactical guidance. If applicable, an alert was issued one minute prior to predicted collision zone entry (considered on the timeline to be close to the CPA). Note that the loss of separation could shift left or right and occur before or after a collision zone alert, depending on the relative velocity between the two aircraft. For this experiment, a collision zone alert, if issued, normally occurred prior to separation loss. Issuance of this alert did not affect the tactical resolutions.

The experiment focused on maneuvers performed by pilots just prior to when TCAS would have provided an RA. As discussed earlier, TCAS issues RA's between 15 and 35 seconds prior to CPA. Conflict alerts during the experiment occurred mainly between 60-70 seconds prior to the CPA. This timeframe may be considered to be near a transition between separation assurance and collision avoidance. Because TCAS was not incorporated, no explicit effort was made to consider integration of ACAS RA's and ASAS resolutions in this simulation.
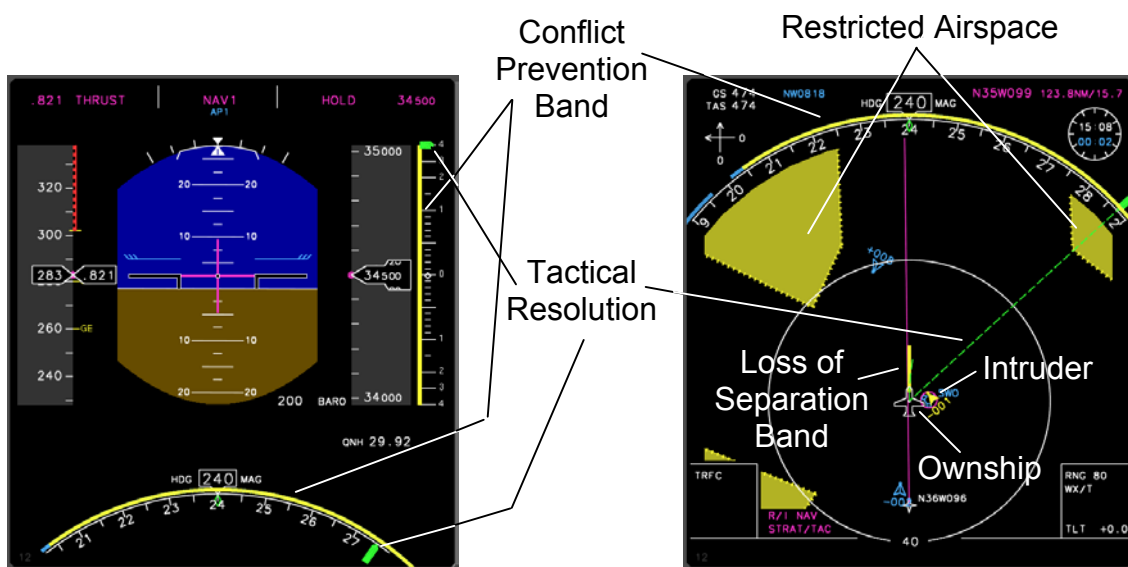
Figure 3. Notional ASAS/ACAS Timeline

Labels in figure: Collision Zone Alert, CPA, Strategic Separation Assurance, Tactical Separation Assurance, TCAS RA, Separation Lost, 2-5, 1, 0, ~0.5, 0, Time to Conflict (min), Time to CPA (min), Experiment's Area of Concentration

Legend:
— Prior to Separation Loss Time to Conflict (min)
······ After Separation Loss
▨ Collision Avoidance Region Time to CPA (min)

Notes: Times Not to Scale
TCAS Not Available for Experiment

Figure 4 shows Primary Flight and Navigation/Traffic Displays as typically seen by the pilot shortly after the intruder aircraft appeared. The intruder was well inside the conflict detection threshold and therefore the conflict alert was generated almost immediately. This alert was shown as an amber band along the ownship's flight path where the separation loss was predicted to occur. The intruder was also color-coded amber to represent its threat level.

When a state-based conflict was detected, pilots were presented with a tactical resolution, shown as green bugs on the vertical speed and heading indicators. The bugs showed the recommended change in either heading or vertical speed needed to resolve the conflict. This resolution guidance allowed the pilot to resolve the conflict by following either the lateral or vertical guidance alone. The resolution algorithm used a modified voltage potential method, originally developed by Eby [15] and refined by the NLR [16]. This algorithm acts to increase the projected separation between the two aircraft at CPA.

Conflict prevention bands were placed on the heading and vertical speed indicators to show headings and vertical speeds that, if flown, would cause a conflict with another aircraft. These bands were predicted using current state information for up to a five-minute time horizon. The heading and vertical speed bands assumed a constant ground speed maneuver in either the horizontal or vertical plane, respectively. A change in speed or a combined lateral/vertical maneuver would change the conflict prevention bands.

**Figure 4. Primary Flight (left) and Navigation (right) Displays**

Labels in figure: Conflict Prevention Band, Restricted Airspace, Tactical Resolution, Loss of Separation Band, Intruder, Ownship

Because the intruder in the conflict scenarios always appeared close to the ownship, a highly aggressive maneuver was required to avoid a separation violation. Avoiding separation loss was designed to be nearly impossible for the scenarios used in this experiment.

Results

Performance Metrics

A single parameter that combines the relative lateral and vertical distances between the ownship and intruder aircraft was used as a measure of threat severity. This parameter, referred to as *epsilon* (ε), is discussed by den Braven [17]. It represents the ellipse distance of an ellipsoid enclosed within the cylindrical separation zone.

Figure 5 shows a cross-section of this geometry for an ellipsoid corresponding to a 5 NM separation standard. The lengths of the ellipsoid's major and minor axes are the separation zone's diameter and total height, respectively. When $\varepsilon=1$, an aircraft is on the surface of the ellipsoid centered on another aircraft. Once inside the separation zone, threat severity increases as ε approaches zero.

Figure 5. Ellipsoid and Cylindrical Separation Zone

In order to compare results from the 3 and 5 NM scenarios, all results using ε were calculated with a 5 NM separation zone. With this convention, the same value of ε corresponded to the same threat level for both separation standards. For cases where the tested separation zone was 3 NM, $\varepsilon<1$ did not necessarily imply a separation violation (Figure 5, Region A). Conversely,

a separation violation may still have occurred when $\varepsilon>1$, for cases where the aircraft was outside the ellipsoid, but within the separation zone cylinder (Figure 5, Region B).

Two performance metrics were considered for the experiment:

- Threat Proximity (ε_{min}): actual minimum ε between the two aircraft.

- Risk Mitigation (ε_{diff}): difference between the predicted minimum ε at the time the alert was issued (based on current state information for both aircraft) and ε_{min}.

Threat Proximity

Figure 6 shows ε_{min} for the 3 and 5 NM separation cases, broken down by whether the pilot *complied* or *did not comply* with the tactical resolution. The pilot was said to *comply* if his initial maneuver (either lateral or vertical) was in the same direction as the corresponding tactical resolution. Using this definition, the pilot *complied* 9/15 (60%) times for the 3 NM separation zone and 13/16 (81%) times for the 5 NM zone. Note that one 3 NM separation scenario was lost due to an earlier pilot maneuver that prevented the planned conflict from taking place.

Note: Error bars represent 1 standard error of the mean.

Figure 6. Minimum Epsilon by Separation Zone Size and Tactical Resolution Compliance

The lateral separation zone distance did not appear to affect threat proximity. No significant differences were found for ε_{min} between the 3 and 5 NM separation cases when combined over pilot compliance.

A linear regression of tactical guidance compliance (combined across separation zone conditions) onto ε_{min} was performed. The regression showed that compliance could significantly predict ε_{min} ($F(1, 29) = 4.264$, $p < .05$, $R^2_{adj} = .098$) and that ε_{min} was larger for those who complied ($M = .497$, $SD = .310$, $n = 22$) than for those who did not comply ($M = .266$, $SD = .193$, $n = 9$). Observed power $(1 - \beta)$ was .515.

Risk Mitigation Due to Maneuver

Whereas ε_{min} is a measure of maximum threat severity, ε_{diff} can be used to assess a pilot's ability to improve the conflict situation over that predicted when the alert was first issued. Epsilon$_{diff}$ is a more suitable metric for comparing pilot performance because it accounts for any differences in predicted ε_{min} that may have occurred due to different initial conflict geometry. Although the experiment was designed to generate the same initial conditions (approach angle and time to closest point of approach) across all scenarios, prior maneuvers by the subject pilot caused differences in a few cases. On average, however, these differences were minimal. Predicted ε_{min} at the time of the alert ranged from 0.01 for the 3 NM/did-not-comply scenarios to 0.07 for the 5 NM/comply cases, with an overall mean across all scenarios of 0.04.

Figure 7 shows ε_{diff} as a function of separation zone size and resolution compliance. A linear regression of tactical guidance compliance (combined across separation zone conditions) onto ε_{diff} showed that compliance could marginally predict ε_{diff} ($F(1, 29) = 3.118$, $p = 0.088$, $R^2_{adj} = .066$) and that ε_{diff} was marginally larger for those who complied with guidance ($M = .446$, $SD = .297$, $n = 22$) than those who did not comply ($M = .256$, $SD = .192$, $n = 9$). Observed power $(1 - \beta)$ was .400. This result was not significant at the $\alpha = .05$ level used for the present study.

The lateral separation zone distance did not appear to affect the pilot's risk mitigation. No significant differences were found for ε_{diff} between the 3 and 5 NM separation cases when combined over pilot compliance.
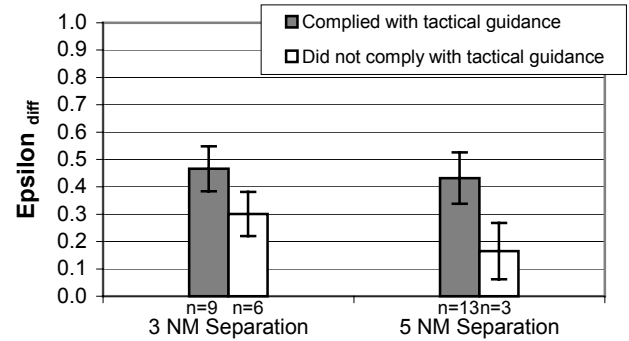
Note: Error bars represent 1 standard error of the mean.

Figure 7. Differences between Actual Minimum Epsilon and Minimum Epsilon Predicted when Alert Issued, by Separation Zone Size and Tactical Resolution Compliance

Pilot Questionnaires

Post-scenario questionnaire results related to the decision support tools and the pilots' perceived operational safety are shown in Table 1. Each question had a 1 to 7 rating scale, ranging from 1 (least favorable) to 7 (most favorable). The scale description as applied to each question is given in the 2nd column of Table 1.

Table 1. Pilot Questionnaire Results

Question	Rating Scale	Overall Mean
How intuitive was the conflict alerting system?	1: not at all intuitive → 7: very intuitive	5.0
How acceptable were the tactical resolutions?	1: not at all acceptable → 7: completely acceptable	4.3
What was the level of safety for this scenario?	1: completely unsafe → 7: completely safe	4.0
How did the conflict manage-ment tools affect the risk level?	1: greatly increased risk → 7: greatly decreased risk	4.8

Results suggest that pilots had a weak acceptance of the conflict alerts and resolutions. These results may be partially due to pilots only having an opportunity to use the ASAS tools during high-risk short-term conflicts. Potential design changes to the ASAS tools currently

under consideration and discussed below may also improve these ratings for future studies. It is not surprising that pilots felt neutral about the level of safety corresponding to a pop-up conflict. These conflicts were designed to pose a safety hazard associated with a non-normal event.

The DAG-TM concept incorporates several safety measures to reduce the likelihood of the type of scenario evaluated in this experiment [1]. Before maneuvering, pilots of autonomous aircraft must ensure that they do not create near-term conflicts. Refined ASAS tools relying on highly dependable surveillance systems should provide these aircraft with adequate warning of upcoming conflicts in all nominal cases. During normal operations, pilots of both aircraft will have the necessary tools to resolve conflicts. New decision support tools are also expected to enable air traffic service providers to provide separation services for aircraft not equipped for autonomous operations.

Discussion

Reducing the lateral separation from 5 to 3 NM did not appear to increase operational risk for the near-term conflicts studied in this experiment. Additional studies could consider whether any reduction in alert and subsequent maneuver times would lead to lower risk in cases where a conflict situation exists prior to the alerting time horizon. Because a 3 NM separation zone represents a smaller target, trajectory uncertainties may cause a shorter alert time when compared to a 5 NM zone. A smaller separation zone may also reduce the number of alerted conflicts that evolve into safety critical situations. Due to the consistent alert time associated with the pop-up conflicts in this experiment, no such changes could be observed. As discussed earlier, extensive analysis is also needed to determine whether surveillance system performance can support lower separation minimums.

Pilots were able to reduce threat severity and mitigate risk in response to pop-up conflicts more effectively when they followed the tactical guidance from ASAS. In order to further improve upon those results, several design enhancements could be considered for the conflict resolution system. These changes could tap into extensive development and evaluation of TCAS.

As the time to closest point of approach decreases, it becomes more important for the ASAS resolutions to be compatible with RA's that are eventually provided by ACAS [8]. TCAS design goals that could be considered for ASAS enhancement include: attempt to avoid crossing the intruder's altitude (especially for very close encounters), provide a resolution that does not require the ownship to change direction, allow time for each aircraft to initiate a maneuver prior to reversing the RA, and avoid reversing the RA unless needed to ensure safety [4, 18-19]. These design goals are likely extensible to both lateral and vertical maneuvers. For example, previous studies have shown that pilots are less likely to turn toward the intruder as they get closer to the conflict [20].

In addition to the desirable goal of more compatible ASAS and ACAS systems [6, 10, 21], enhancements to the ASAS tools that consider pilot maneuver preferences when possible would also likely increase the compliance rate and response time [22]. Previous studies have shown that pilots are more likely to comply promptly and correctly with resolution commands when the guidance supports their maneuver tendencies [22-23].

Conclusions

For near-term conflicts, a pilot's ability to reduce threat proximity and mitigate risk appears to depend more on compliance with the ASAS resolution guidance than on the size of the lateral separation zone. Compliance with the tactical resolutions led to improvement in threat proximity and risk mitigation. These positive effects may be further increased by design enhancements to the ASAS conflict resolution system.

Before air-air separation assurance or other applications with lower separation minimums are implemented, a thorough Operational Safety Assessment will need to be performed. This process has been described by Zeitlin [8]. Included in this process is an Operational Hazard Analysis where potential hazards, the operational effects of those hazards, and mitigation strategies are assessed. Evaluation of pilot performance using ASAS tools will likely be an important part of this process.

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Key Words

ACAS, ASAS, collision avoidance, DAG-TM, safety, separation assurance

Author Biographies

Mr. Barhydt has a B.S. in Aerospace Engineering from the University of Colorado (1995) and an S.M. in Aeronautics and Astronautics from MIT (1997). He is an aerospace engineer at the NASA Langley Research Center, working on the Advanced Air Transportation Technologies project. He has experience in Flight Management System operations and has conducted experiments on the use of intent information on cockpit traffic displays. He is a certified instrument flight instructor and commercial pilot for single engine aircraft. He is also a member of RTCA Special Committee 186, Working Group 4 (Application Technical Requirements) and Working Group 6 (ADS-B MASPS Revision A).

Dr. Eischeid is currently a senior consultant for Booz-Allen & Hamilton. He holds a Ph.D. in Human Factors Psychology from Old Dominion University with a graduate minor in computer simulation and modeling. He currently supports feasibility studies of the DAG-TM concept in the areas of human factors design, experimental design, and statistical analyses.

Mr. Palmer is an Aerospace Engineer in the Crew Systems Branch at NASA Langley Research Center, and has been investigating advanced flight deck concepts and technologies since 1985. He holds a B.S. in Aerospace Engineering from Auburn University, an M.S. in Computer Science from the College of William and Mary, and is currently ABD in the Industrial and Systems Engineering Ph.D. program at the Georgia Institute of Technology. He is a Senior Member of the American Institute of Aeronautics and Astronautics (AIAA), and is a member of both the Association for Computing Machinery (ACM) and the Human Factors and Ergonomics Society (HFES). He is also an instrument-rated private pilot.

Mr. Wing is a research engineer in the Aviation Operations and Evaluation Branch at the NASA Langley Research Center. Through NASA's Advanced Air Transportation Technologies project, he contributed to the detailed development of the "Distributed Air/Ground Traffic Management" (DAG-TM) concept and research plans, and is currently Langley's Principal Investigator for DAG-TM Concept Element 5 feasibility research. He holds an M.S. in Aeronautical Engineering and a B.S. in Mechanical Engineering, and he is an instrument-rated private pilot.